Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 67 (2015) 491 – 496
Physics Procedia

25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

Development of compact 2K GM cryocoolers

Mingyao Xu[a] Qian Bao[a], Akihiro Tsuchiya[a], Rui Li[b]

[a]*Technology Research Center, Sumitomo Heavy Industries, Ltd., 2-1-1, Yato-cho, Nishitokyo-city, Tokyo 188-8585, Japan*
[b]*Precision Equipment Group, Sumitomo Heavy Industries, Ltd., 2-1-1, Yato-cho, Nishitokyo-city, Tokyo 188-8585, Japan*

Abstract

A compact 2K Gifford-McMahon (GM) cryocooler has been developed for cooling electronic devices, such as Superconducting Single Photo Detectors (SSPD). The heat exchangers, regenerators are optimized with the numerical simulation method developed for 4K GM cryocoolers. After optimizing, the cylinder length is reduced by 85 mm compared with a commercial 0.1W 4K GM cryocooler. With no load on the second stage, a temperature of about 2.1 K has been achieved. With 1 W and 20 mW heat load, the temperature is 44.4 K at the first stage and 2.23 K at the second stage with an input power of about 1.1 kW. And also, it is found that the temperature oscillation decreases as the average temperature decreases. A temperature oscillation of about ±20 mK has been achieved. The object of the project, target specification, and a summary of experiment results will also be introduced in this paper.

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014

Keywords: Simulation; Regenerator; Temperature Oscillation; Gifford-McMahon cryocooler; Cryocooler.

1. Introduction

Since 1990, the efficiency of a 4K GM cryocooler has been continuously improved by optimizing the operation parameters by Kuriyama et al. (1996) and valve timing by Li et al. (1996), etc. Recently, the efficiency of 4K GM cryocoolers has been further improved by about 30% by Xu and Morie et al. (2012).

Corresponding author: Mingyao Xu. Tel: +81-42-468-4474; fax: +81-42-468-4477.
Email address: Mgy_Xu@shi.co.jp

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014
doi:10.1016/j.phpro.2015.06.064

1.1. Background

4K GM cryocoolers manufactured by Sumitomo Heavy Industries, Ltd. (SHI) have been widely used for cooling superconducting magnet in various applications and research projects, such as an MRI system. For these systems, the requirement to have a compact size cryocooler is not critical because the size of the magnet itself generally is quite large. On contrast, for a superconducting electronic device, such a requirement becomes crucial. Indeed, comparing with a similar semiconductor device, the size of a superconducting electronic device, including the cryostat, is comparably large. A good example of superconducting electronic devices is SSPD, which is now under development at National Institute of Information and Communications Technology, Japan. Miki et al. (2010, 2012).

Compared with a semiconductor detector, the size of an SSPD system and the input power consumption are too large, which are the major obstacles to expand the application of a SSPD.

In order to provide a cooling solution which can meet the new demand by such applications, we have developed a new compact 2K GM cryocooler system which can reach 2.10 K under no-load condition and yet being highly compact in physical size. This development was carried out as a part of the project, "Development of a Compact Superconducting Single Photon Detector System for Photon-Quantum Information and Communication".

The simulation method, the approaches and the results of improved unit performance and the length reduction of the cylinder will be reported in this paper.

1.2. Design Target

We chose a RDK-101D as our development base since it has been the smallest 4K GM cryocooler in the world. Thus, this cryocooler would be a good start point for further improvement. The basic specification of RDK-101D and design target for the new 2K GM cryocooler is shown in Table 1 below.

Table 1. Design target of the new 2K GM cryocooler.

Item	RDK-101D	Development Object
First stage cooling capacity at 60 K	3 W	1 W
Second stage cooling capacity at 2.3 K	Unreachable	20 mW
No-load second stage temperature	Over 3 K	2.2 K
Expander height	442 mm	67% of RDK-101D
Temperature oscillation	Over ±30 mK	±20 mK

Considering the targeted cooling application, we set the design temperature targets of the first and the second stages under 1 W and 20 mW of the thermal load to be 60 K and 2.3 K respectively. It is known that the measurement accuracy of an SSPD increases greatly as the temperature decreases. Therefore, the target of no-load temperature is set to 2.2 K. On the other hand, since the heat load to the second stage is reduced significantly, the cooling capacity of 20 mW at 2.3 K seems to be large enough for such devices. Both the no-load temperature and the cooling capacity at 2.3 K are difficult to achieve since the lamda point of helium 4 is around 2.05 K at 1.1 MPa. The latter is the estimated low pressure at the second stage expansion space.

The temperature oscillation is designed to be under ±20 mK. The most challenging objective is to reduce the expander height to 67% relative to the existing RDK-101D GM cryocooler. The details on the approaches for reducing the expander height will be described in the cylinder length reduction section.

2. Simulation

2.1. Simulation method

We reported a simulation method and confirmed the accuracy of the simulation results by comparing them with the results obtained for a 1W 4K GM cryocooler. The simulation method has been verified to be an effective way to improve the efficiency of a 4K GM cryocooler. In the simulation model, a two-stage G-M cryocooler is divided into many elements and the state in each element can be calculated by solving the basic equations. Xu et al. (2012).

2.2. Simulation conditions

In order to confirm the accuracy of the simulation method for a small-size GM cryocooler, simulations have been performed using the parameters of an SHI 0.1W 4K two-stage GM cryocooler RDK-101D. For typical calculations, the cold-head is operated at 1.0 Hz, the high and low pressures at the inlet of the rotary valve are 2.28 MPa and 0.89 MPa, respectively.

The inner diameters of the first and second stage cylinder are 44 mm and 18 mm, respectively. The first stage regenerator is filled with #150 phosphorous bronze screens. The second stage regenerator is filled with lead and $HoCu_2$ spheres. The porosity of the second stage regenerator is assumed to be 0.3 for all calculations. The average sphere diameter is 0.44 mm for lead and 0.33 mm for $HoCu_2$.

2.3. Simulation results

Table 2 shows simulation results of the P-V power, the cooling capacity and the losses. The temperatures are assumed to be 45 K at the first stage and 4.2 K at the second stage. The compressor is operated at 50 Hz and the cold head is operated at 1.0 Hz. As shown in Table 2, the P-V power is 17.5 W at the first stage and 3.27 W at the second stage. The cooling capacity after considering real gas effect is 17.2 W and 0.56 W, respectively. The cooling capacity after considering real gas effect at the second stage is much lower than the P-V power because the properties of helium at the second stage temperature are significantly different from those of an ideal gas. Xu et al. (1999). A large amount of extra enthalpy flow enters into the second stage expansion volume from the second stage regenerator, which reduces the cooling capacity significantly. Xu et al. (2012). The regenerator loss is 3.5 W at the first stage and 0.24 W at the second stage. The Shuttle losses are 1.8 W and 0.06 W, respectively. The enthalpy flux from the clearance between the cylinder and the displacer, which includes the pumping loss and thermal conduction loss, is 3.2 W and 0.20 W. The radiation loss is 1.5 W at the first stage and negligible at the second stage. As a result, the net cooling capacity is 7.1 W at the first stage and 0.06 W at the second stage.

It is obvious that for both stages, the largest loss is due to the regenerator losses. In addition, it should be pointed out that, unlike a large-size GM cryocooler, the thermal conduction loss and the radiation loss are relatively large and should be reduced in order to further improve the cooling capacity.

The average cooling capacity, measured with two RDK-101D GM cryocoolers, is 3.0 W at 45 K at the first stage and 0.14 W at 4.2 K at the second stage. Although there is still some differential between the simulation and experimental results, the simulation results accuracy is good enough for parameters and configuration optimization.

Table 2. Simulation results of cooling capacity and losses of a small-size 4K GM cryocooler.

Item	First stage at 45K (W)	Second stage at 4.2 K (W)
P-V power	17.5	3.27
Cooling capacity after considering real gas effect	17.2	0.56
Regenerator loss	3.5	0.24
Shuttle loss	1.8	0.06
Pumping loss & thermal conduction loss through walls	3.2	0.20
Radiation loss	1.5	0.0
Net cooling capacity	7.1	0.06

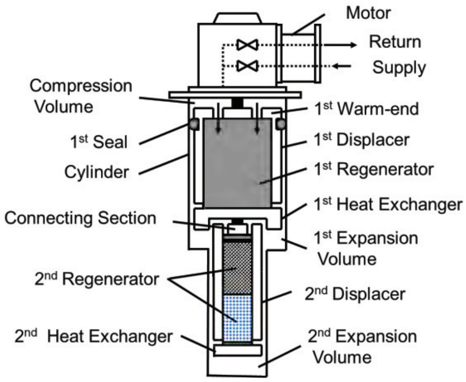

Fig. 1. Schematic diagrams of a two-stage GM cryocooler.

3. Experiment results

3.1. Performance improvement

Fig. 1 shows schematic diagrams of a typical two-stage GM cryocooler. As shown in Fig. 1, most of the expander height is dominated by the first and the second stage regenerators. In order to reach the height reduction target, the length of the regenerators must be reduced. However, if the regenerator length is shortened, the regenerator loss will increase. Accordingly, the net cooling capacity will decrease. At the beginning of the development, bismuth was supposed to be used as a regenerator material at the warm-end of the second stage regenerator in order to be complied with RoHs regulation. Shortly after the project was launched off, a new regenerator material, which can be used at the warm end of the second stage regenerator, has been found. The no-load temperatures of a prototype unit with this new material and those with bismuth are shown in Table 3. As shown in Table 3, with bismuth, the no-load temperature is 45.7 K at the first stage and 2.46 K at the second stage. With the new material, the no-load temperature is 42.2 K at the first stage and 2.41 K at the second stage. With the new material, the no-load temperature decreases about 3.5 K at the first stage and about 0.05 K at the second stage. The reason of such a performance improvement is that the temperature profile of the regenerator was shifted to a high temperature level when the new regenerator material was used. Accordingly, the average temperature in the second stage regenerator increased and a smaller amount of gas was needed to fill the void volume of the second stage regenerator. Xu et al. (2014).

Table 3. No-load temperatures with respect to the type of regenerator material at the warm end of the second stage regenerator.

Regenerator material	First stage temperature (K)	Second stage temperature (K)
Bismuth	45.7	2.46
New material	42.2	2.41

As to the cold end of the second stage regenerator, part of $HoCu_2$ is replaced by Gd_2O_2S (GOS). Numazawa et al. (2003). With GOS at the cold end, the no-load temperature reduces by about 0.1 K.

3.2. Cylinder length reduction

In order to reduce the expander height to 67% relative to the existing RDK-101D GM cryocooler, a series of fundamental research was performed.

The simulation method, as described above, was used to optimize the volume ratio of the regenerator materials to reduce the regenerator loss. The length of the first and the second stage heat exchangers, and the regenerators were also optimized with the simulation method.

Additionally, the seal configuration at the warm-end of the first stage displacer was optimized to minimize the length at the warm-end. Also, a novel configuration connecting the first and the second displacers has been developed to minimize the length of the connecting section.

The length reduction of major components and the total length reduction of the cylinder are shown in Table 4. As shown in Table 4, by optimizing the seal configuration at the warm end of the first stage and the stroke, the cylinder length is reduced by about 9 mm. By optimizing the length of the first regenerator and the heat exchanger with the simulation method, the cylinder length is reduced by about 28 mm and 5 mm, respectively. The length of the connecting section between the first displacer and the second displacer is reduced by about 21 mm with the novel connecting configuration. As to the second stage, a new regenerator material is adopted. With this new regenerator material, the temperature profile of the second stage regenerator is improved. And also, the volume ratio of the regenerator materials is optimized. Accordingly, the cooling performance of the second stage is improved and the length of the second stage can be reduced without performance degradation. As a result, the length of the cylinder is reduced by about 10 mm. Furthermore, by optimizing the length of the heat exchanger at the cold end of the second stage and the flow passage at the cold end, the length of the cylinder is reduced by about 12 mm.

Table 4. Length reduction of major components of the cylinder.

Item	Length Reduction	Approach
First stage warm-end	5 mm	Design optimization
Stroke	4 mm	
First stage regenerator	28 mm	Optimized by simulation
First stage heat exchanger	5 mm	
Connecting section	21 mm	New configuration
Second stage regenerator	10 mm	New regenerator material
Second stage heat exchanger	12 mm	Optimized by simulation
Total	85 mm	

3.3. Cooling performance of a prototype unit

The performance of a prototype unit of the newly developed 2K GM cryocooler is shown in Table 5. As shown in Table 5, a cooling capacity of 1 W @ 44.4 K has been achieved at the first stage. That should be compared to the goal, which was set at 1 W @ 60 K. At the second stage, compared to the goal of 20 mW @ 2.3 K, a cooling capacity of 20 mW @ 2.23 K has been achieved. With 1 W and 20 mW heat load, the input power is about 1.1 kW. Under no-load condition, a low temperature of 2.1 K and a temperature oscillation of about ±20 mK have been achieved. For more details on the cool-down curves, the cooling load-map and the temperature oscillation, refer to another paper which will be presented at this conference by Bao et al. (2014).

Table 5. Measured results for a compact 2K GM cryocooler.

Item	Development Object	Measured Results
First stage temperature with 1 W	60 K	44.4 K
Second stage temperature with 20 mW	2.3 K	2.23 K
No-load second stage temperature	2.2 K	2.10 K
Expander height	67% of RDK-101D	81% of RDK-101D
Temperature oscillation	±20 mK	±20 mK

Fig.2 shows the cylinder of a prototype unit compared with that of a RDK-101D GM cryocooler. As shown in Fig. 2, compared to the world smallest 4K GM cryocooler, RDK-101D, the cylinder length has been reduced by about 85 mm.

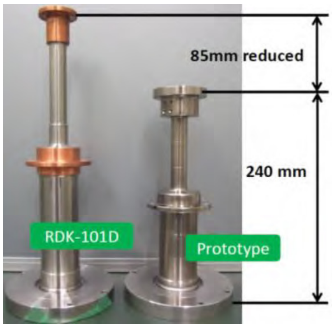

Fig. 2. Cylinders of a prototype unit of the new 2K GM cryocooler and a RDK-101D GM cryocooler.

4. Conclusion

A new compact GM cryocooler has been developed, which can be used for cooling superconducting electronic devices.. The cylinder length is reduced by 85 mm compared with commercially available 0.1W 4K GM cryocooler. Under no-load condition, a low temperature of 2.1 K and a temperature oscillation of about ±20 mK has been achieved. A cooling capacity of 1 W at 44.4 K at the first stage and 20 mW at 2.23 K at the second stage has also been achieved.

In order to reach the expander height reduction target, the height of the valve housing assembly will be reduced together with further cylinder length reduction.

Acknowledgments

The research results have been achieved by "Development of a Compact Superconducting Single Photon Detector System for Photon-Quantum Information and Communication", the National Institute of Information and Communications Technology (NICT), JAPAN.

References

Kuriyama, T., Ohtani, Y., Takahashi, M., et al, 1996. Optimization of Operational Parameters for a 4K-GM Refrigerator, in *"Advanced in Cryogenic Engineering 41"*. In: Kittel, P. (Ed.). Plenum Press, New York, pp.1615.

Li, R., Onishi, A., Satoh, T., Kanazawa, Y., 1996. Influence of Valve Open Timing and Interval on Performance of 4K Gifford-McMahon Cycle Cryocooler, in *"Advanced in Cryogenic Engineering 41"*. In: Kittel, P. (Ed.). Plenum Press, New York, pp.1601.

Xu, M., Morie, T., 2012. Development of High-Efficiency 4K GM Cryocoolers, in *"Proceeding of the 24th International Cryogenic Engineering Conference and International Cryogenic Material Conference"*. In: Funaki, K. et al. (Ed.). Cryogenics and Superconductivity Society of Japan, Tokyo, pp. 403.

Morie, T., Xu, M., 2012. Experimental Investigation of High-Efficiency 4K GM Cryocoolers, in *"Cryocoolers 17"*. In: Miller, S. and Ross, R. Jr (Ed.). ICC Press, Boulder, CO, pp. 247.

Miki, S., Yamashita, T., Fujiwara, M., Sasaki, M. and Wang, Z., 2010. Multichannel SNSPD System with High Detection Efficiency at Telecommunication Wavelength. Optics Letters 35, 2133-2135.

Miki, S., 2012. Single Photon Detecting Technology Based on Superconducting Wire. KARC FRONT 24, 11-13. (in Japanese)

Xu, M., Morie, T., 2012. Numerical Simulation of 4K GM Cryocooler, in *"Cryocoolers 17"*. In: Miller, S. and Ross, R. Jr (Ed.). ICC Press, Boulder, CO, pp. 253.

Xu, M., De Waele, A., Ju, Y., 1999. A Pulse Tube Refrigerator below 2K. Cryogenics 39, 865-869.

Xu, M., Morie, T., 2014. Numerical Simulation of the Second Stage Regenerator in a 4K GM Cryocooler, in *"Advances in Cryogenic Engineering 59"*. In: Wisend II, J. et al. (Ed.). American Institute of Physics, New York, pp. 633.

Numazawa, T., et al., 2003. A New Ceramic Magnetic Regenerator Material for 4K Cryocoolers, in *"Cryocooler 12"*. In: Ross, R. Jr (Ed.). Kluwer Academic/Plenum Publishers, pp. 473.

Bao, Q., Tsuchiya, A., Xu, M., Li R., 2014. Experimental investigation of compact 2K GM cryocoolers, 25th International Cryogenic Engineering Conference and International Cryogenic Materials Conference in 2014, Twente, The Netherlands, paper #109.